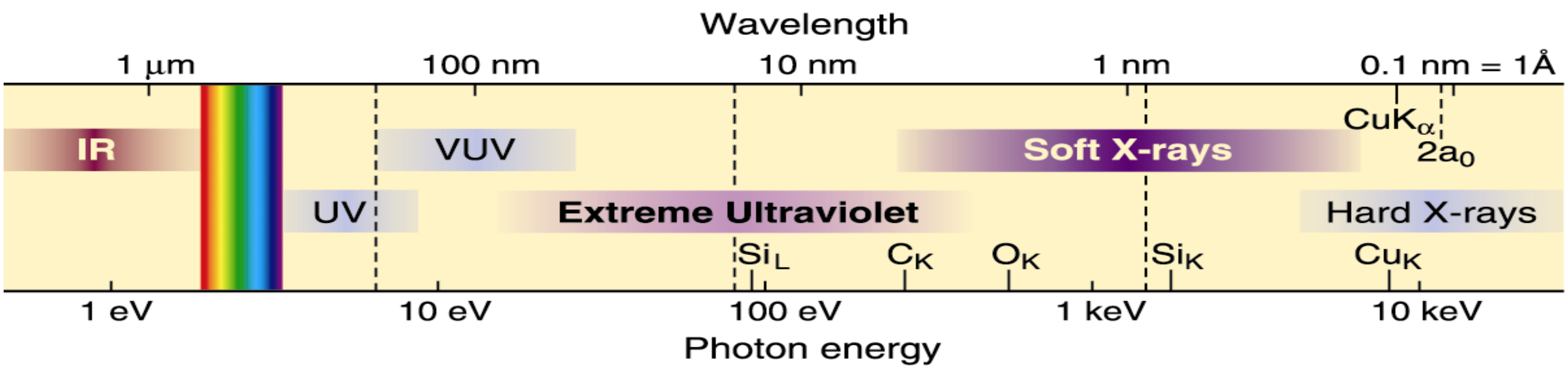
Interferometry, spectroscopy and lensless imaging with extreme ultraviolet radiation

Stefan Witte

Advanced Research Center for Nanolithography
VU University Amsterdam

Extreme ultraviolet radiation

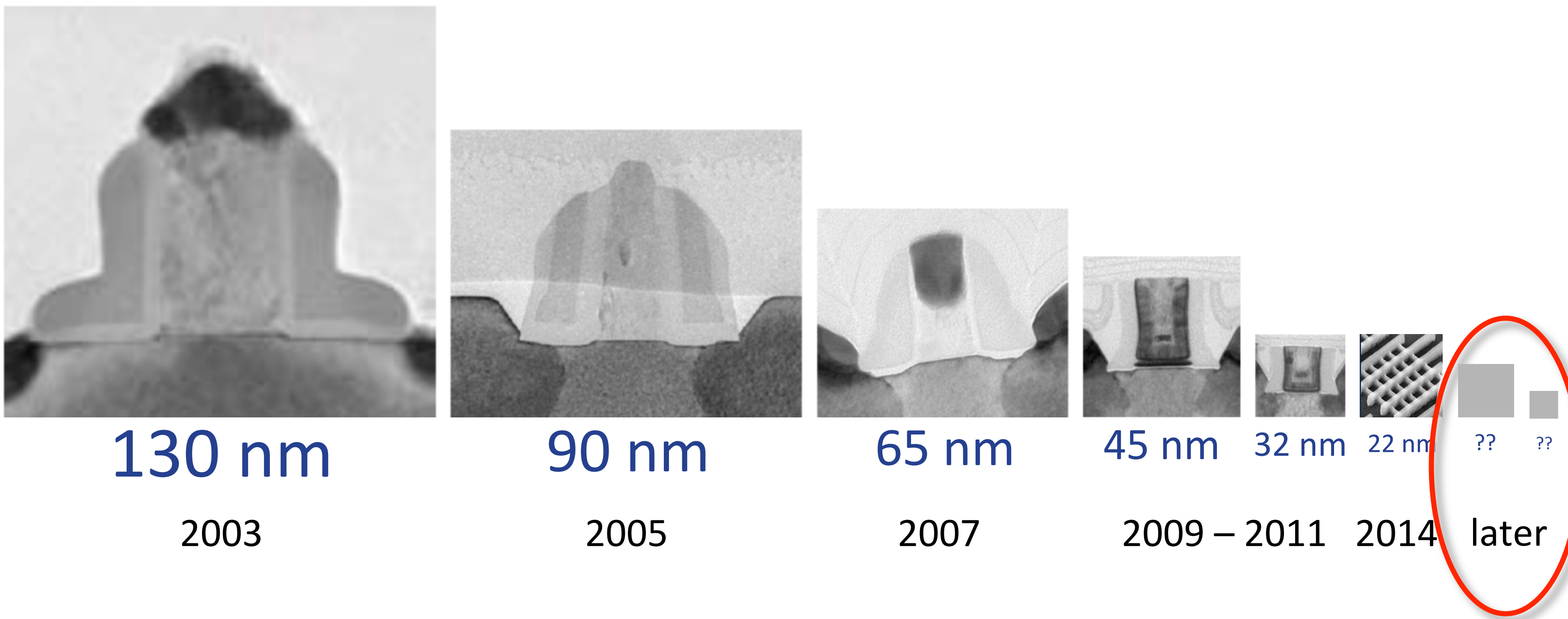


Outline of this talk:

- Extreme ultraviolet radiation and its applications
- High harmonic generation, lasers and EUV spectroscopy
- EUV interferometry and Fourier transform spectroscopy
- Lensless imaging with EUV radiation
- Conclusions

Typical size of lithographic structures

(nano)transistors by Intel

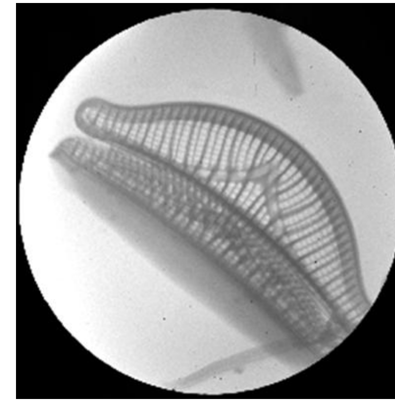


The inside of a chip

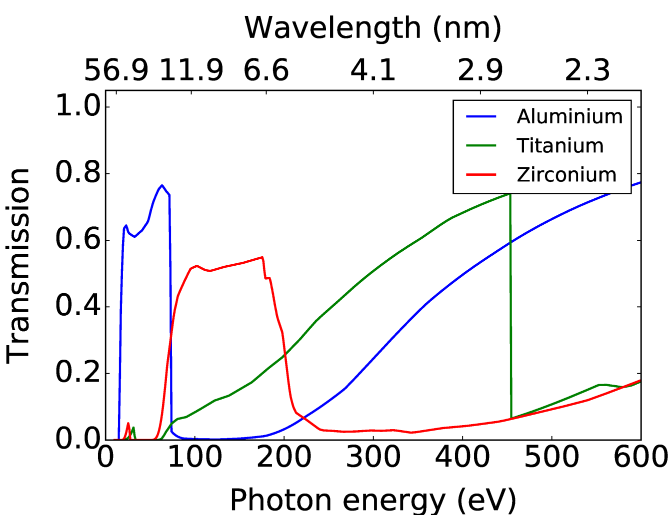
So how do you image this?

Interesting properties of EUV radiation

1) Short wavelength → diffraction from nanoscale objects

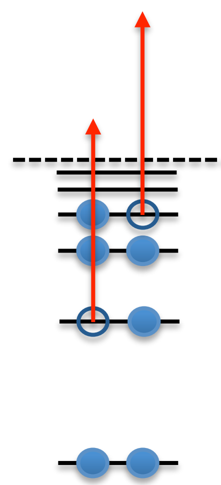


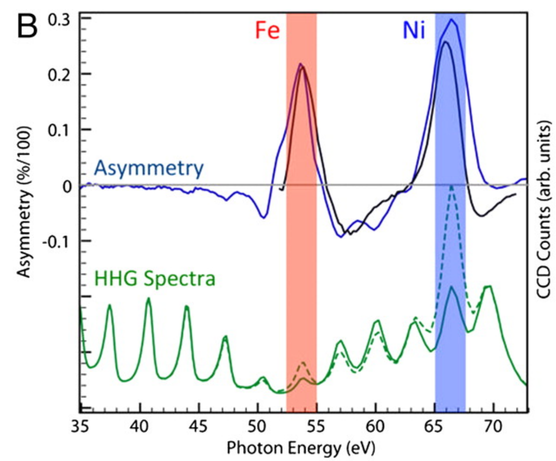
H. Stiel et al., MBI Berlin



2) Element-selectivity → many elements have spectral transmission windows

3) High photon energy → provides access to core levels



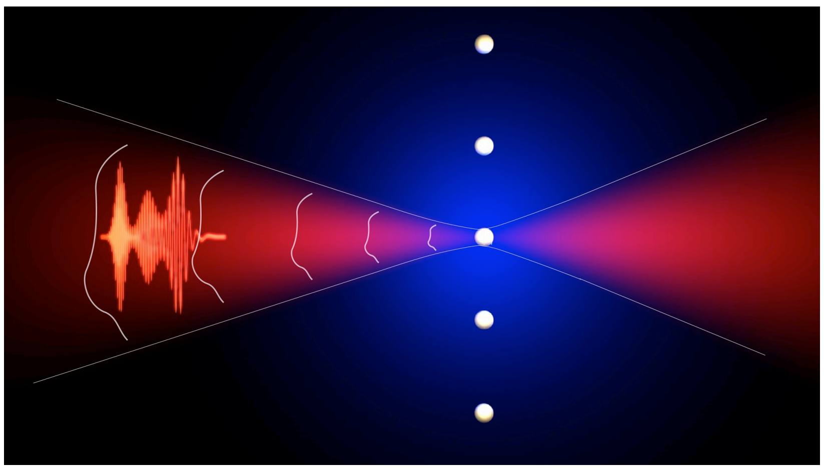


*S. Mathias et al. PNAS **109**, 4792 (2012)*

Table-top EUV sources

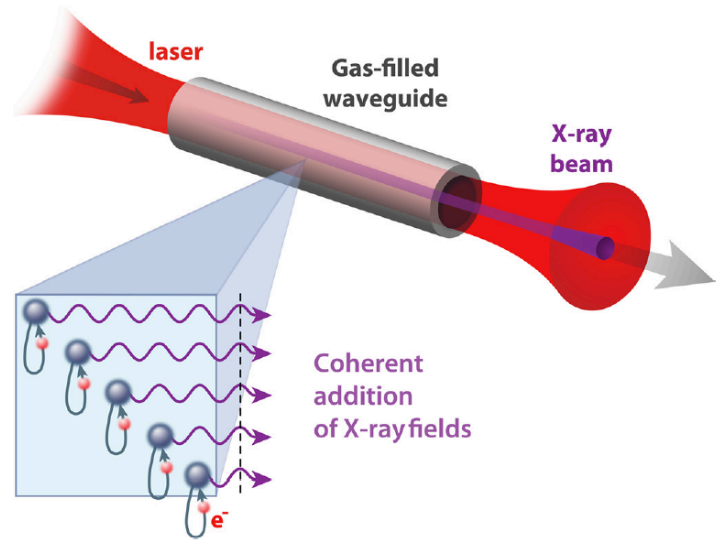
Plasma sources

(pumped by laser or electric discharge)



- Incoherent, 4π emission
- Nanosecond pulses (typical)
- Several % conversion efficiency
- Multiple Watts average power
- Debris from plasma

High-harmonic generation



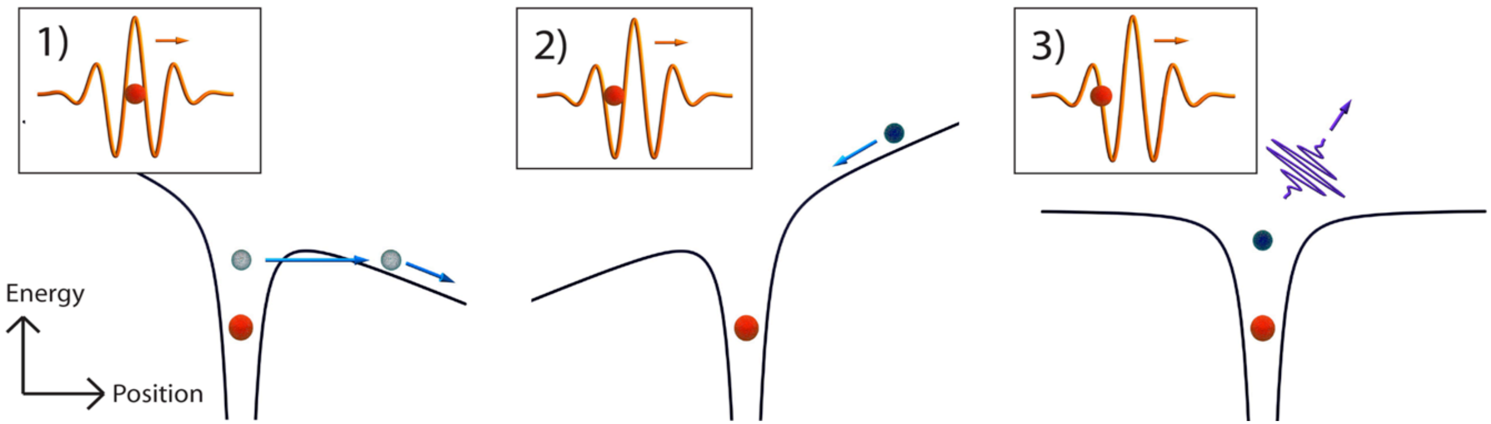
- Coherent, diffraction-limited beams
- Attosecond pulse trains
- Conversion efficiency $10^{-5} - 10^{-9}$
- µW average power
- Need to separate EUV from IR

High harmonic generation

Intense laser modifies Coulomb potential → electron tunnels and accelerates in laser field

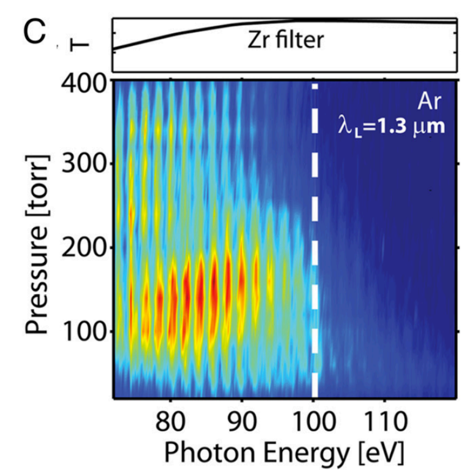
Field changes sign → electron returns to the parent ion

Recollision, electron energy converted into XUV photon



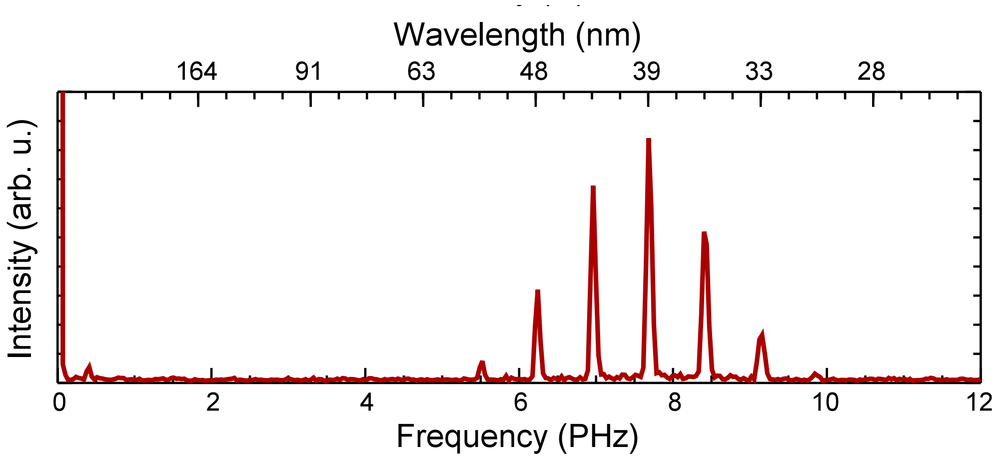
IR and EUV waves need to remain in phase for coherent buildup:

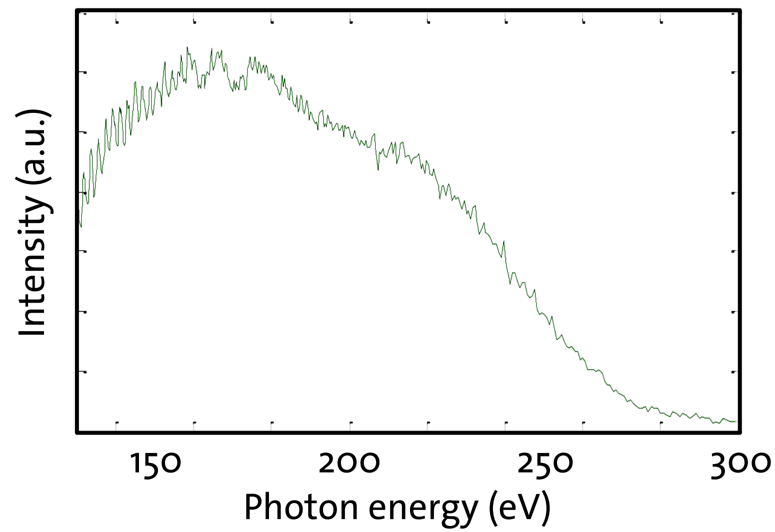
$$\Delta k \approx \underbrace{q\frac{u_{11}^2\lambda_L}{4\pi a^2}}_{\text{geometric}} - \underbrace{qp(1-\eta)\frac{2\pi}{\lambda_L}(\Delta\delta + n_2)}_{\text{atoms}} + \underbrace{qp\eta N_a r_e \lambda_L}_{\text{free electrons}}$$



Need to avoid excessive ionization, limits flux scaling by intensity

Typical HHG spectra





HHG in Argon,

λ_{laser}=800 nm, E=1 mJ, 30 fs

- Series of discrete odd 'harmonics'
- Interference of a train of attosecond EUV bursts, produced every half-cycle

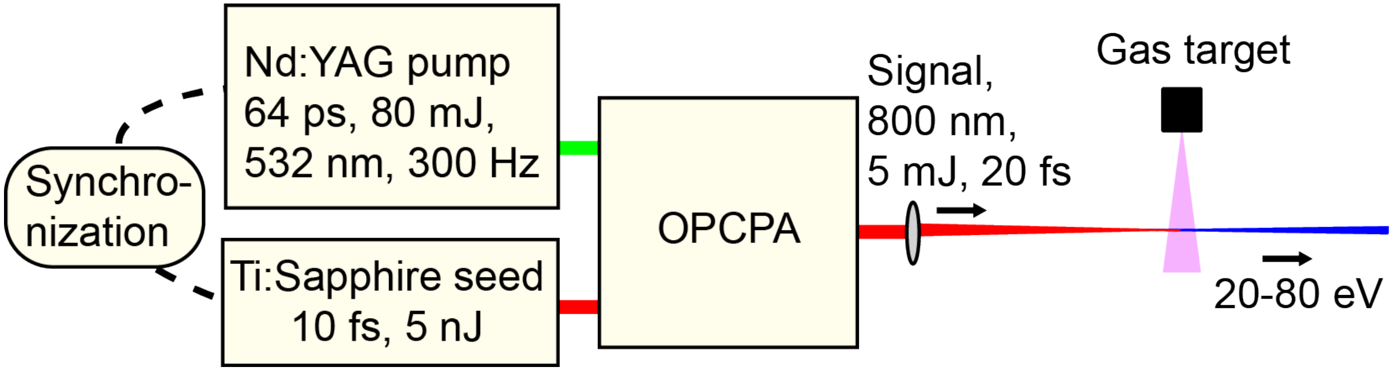
HHG in Helium,

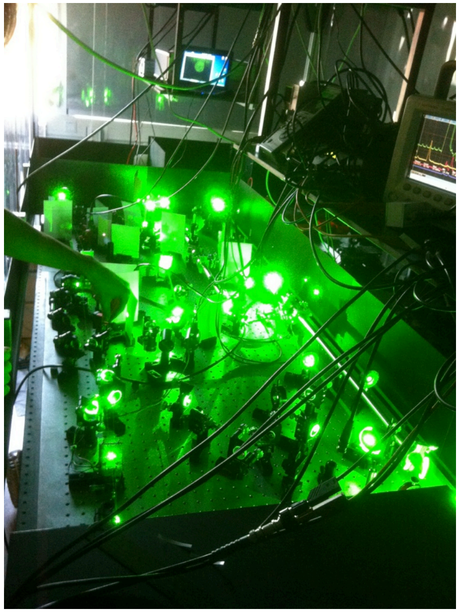
λ_{laser}=1300 nm, E=1 mJ, 40 fs

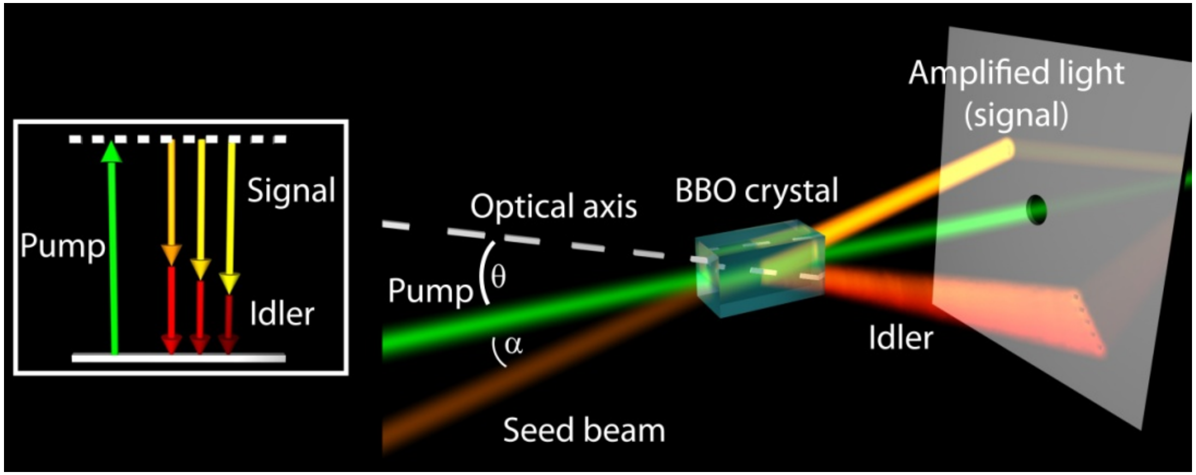
- Harmonics blend into a continuum
- Only few (or one) attosecond bursts

Coherent EUV source development

- Intense few-cycle laser pulses are needed for HHG.
- Produced by optical parametric chirped pulse amplification (OPCPA).





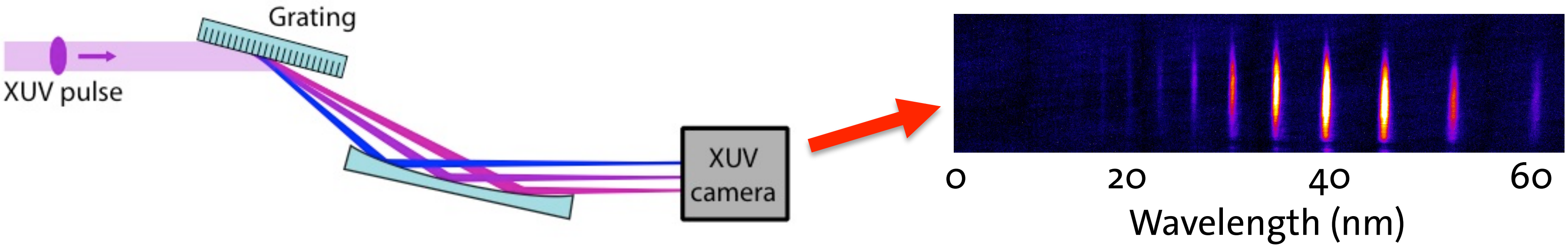


Witte and Eikema, IEEE Sel. Top. Quant. Electron. **18**, 296 (2012)

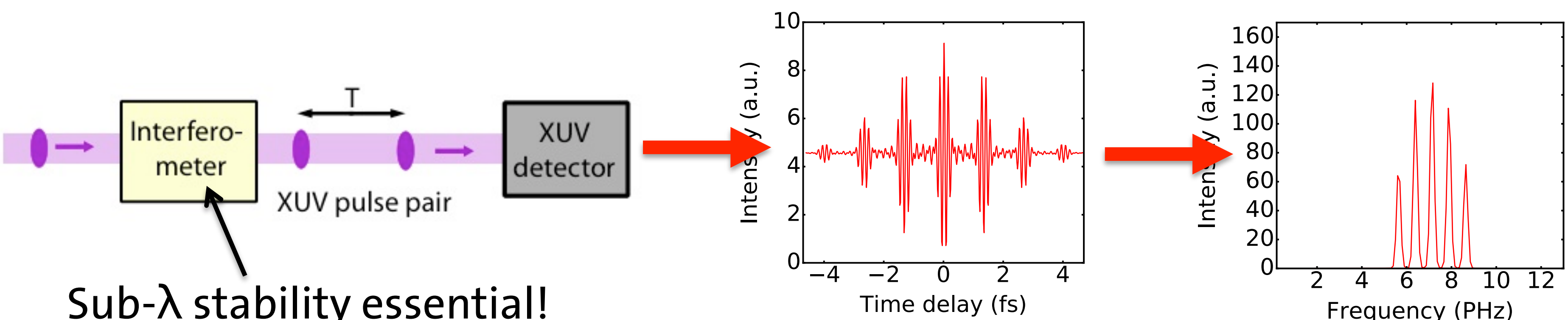
Witte et al., Opt. Express **14**, 8168 (2006)

XUV spectroscopy

Classical grating-based spectrometer: use diffraction to disperse different wavelengths over a spatial axis.

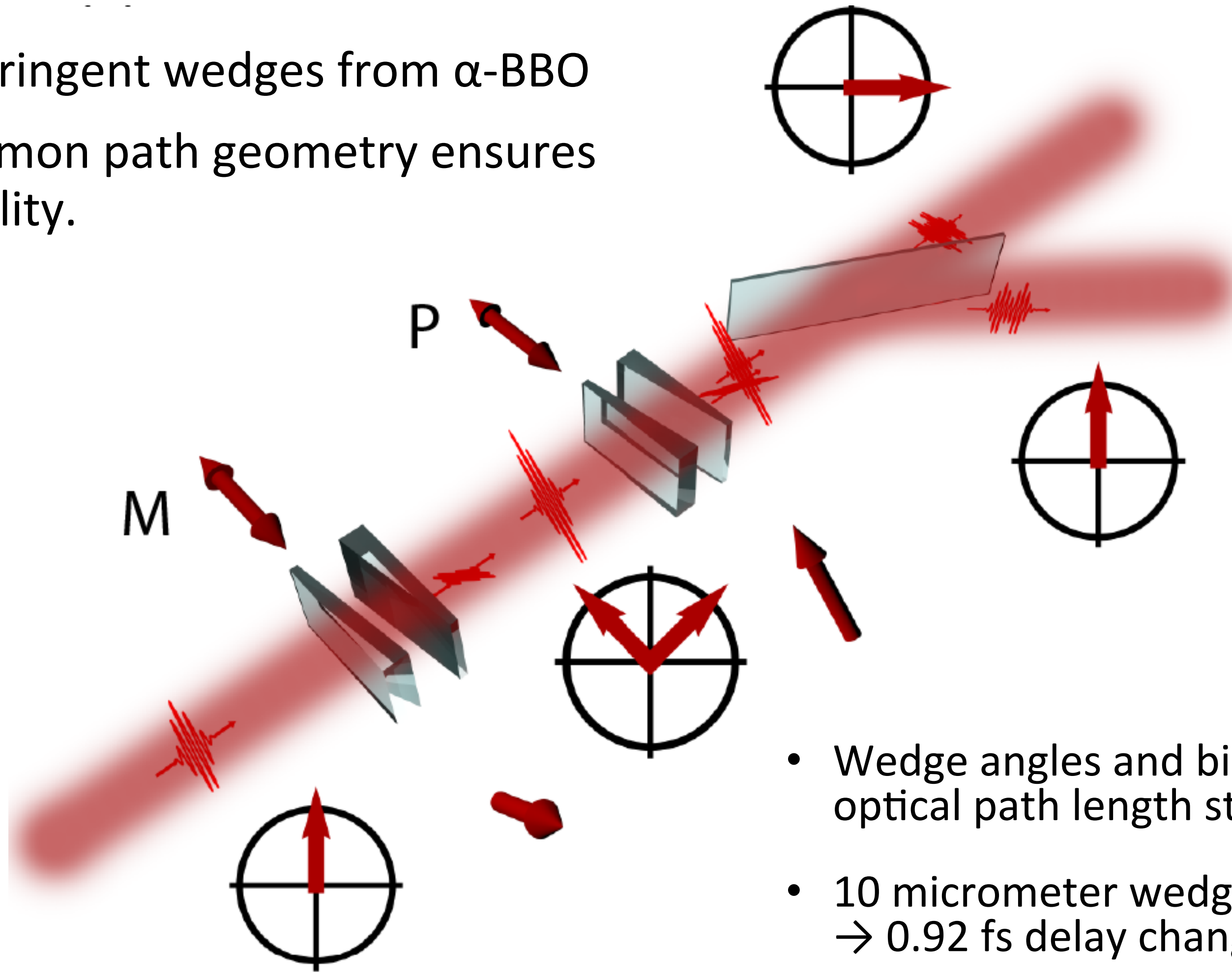


Fourier-transform spectroscopy: measure temporal coherence function and retrieve frequency information by Fourier transform.



Ultra-stable tunable interferometer

- Birefringent wedges from α-BBO
- Common path geometry ensures stability.

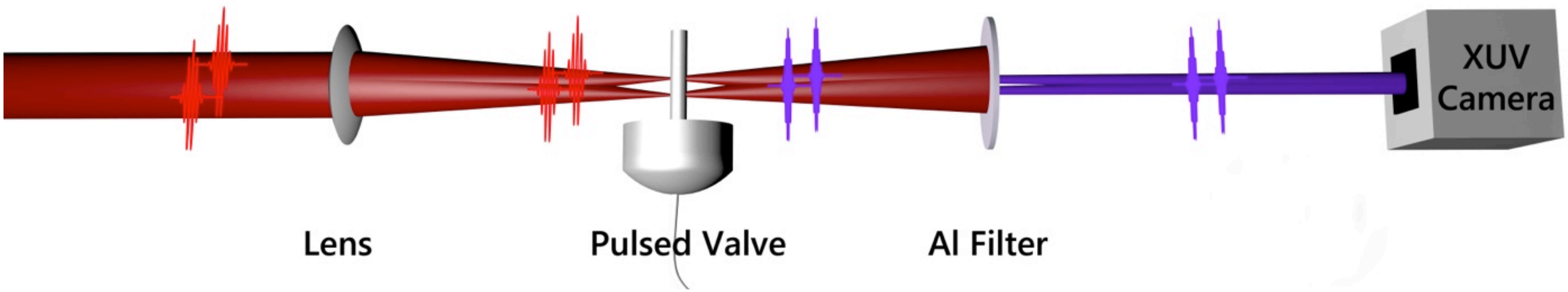


- Wedge angles and birefringence control optical path length step size.
- 10 micrometer wedge displacement → 0.92 fs delay change
- Piezo-stage with 5 nanometer precision → 0.46 attosecond delay steps possible

Brida et al. Opt. Lett. **37**, 3027 (2012)

EUV interferometry

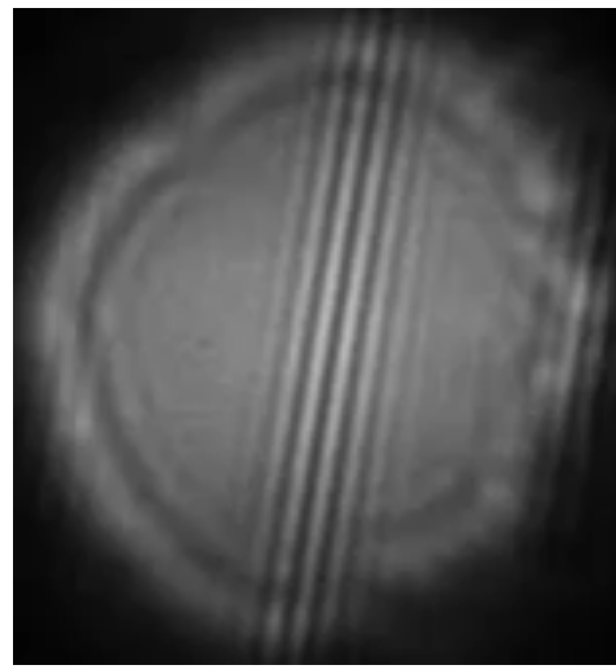
- HHG setup combined with ultra-stable common-path interferometer:



- HHG in Argon with >1 mJ ~20 fs pulses

- Individual pulses should not influence each other during the HHG process → spatially separated HHG zones.

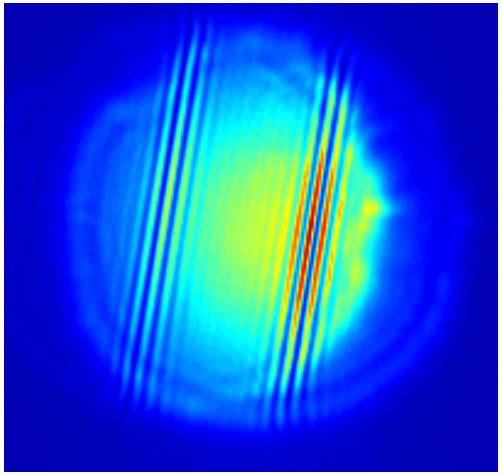
- Collinear beams, overlap after finite distance due to beam divergence.

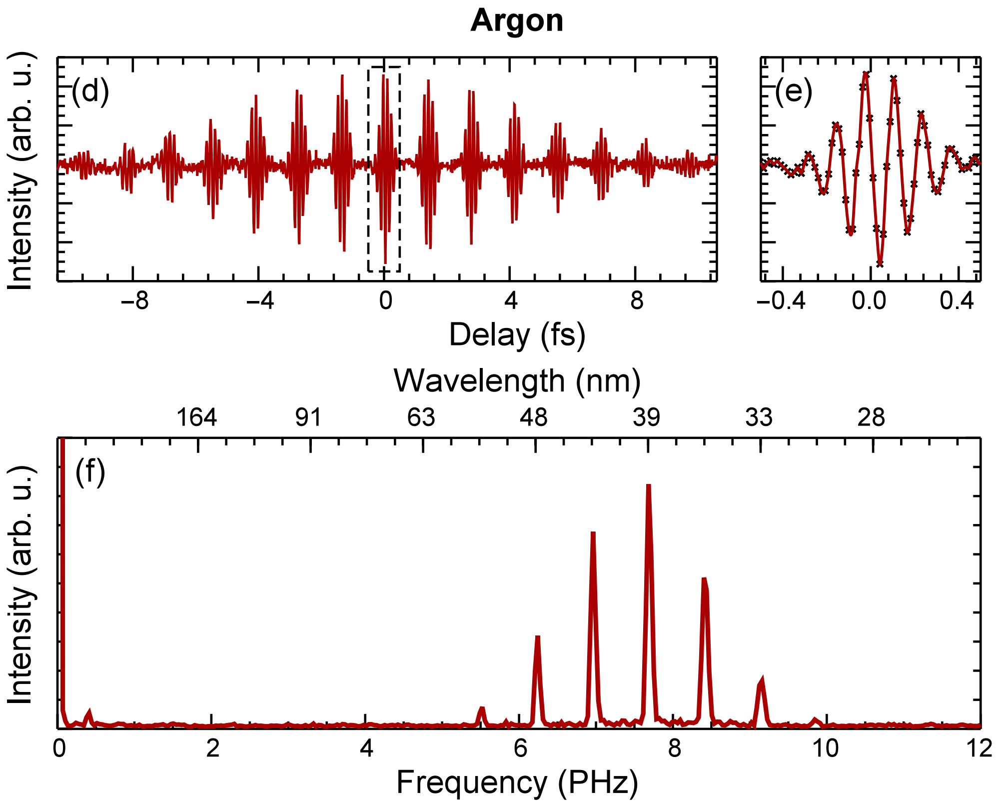


HHG Fourier transform spectroscopy

- Fourier transformation of the time delay scan on a single pixel yields the spectrum at the location of that pixel.
- Linear autocorrelation of two HHG beams yields coherence length.

HHG-FTS in Argon:



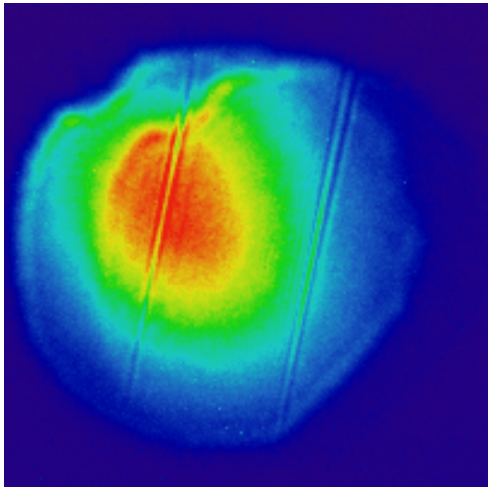


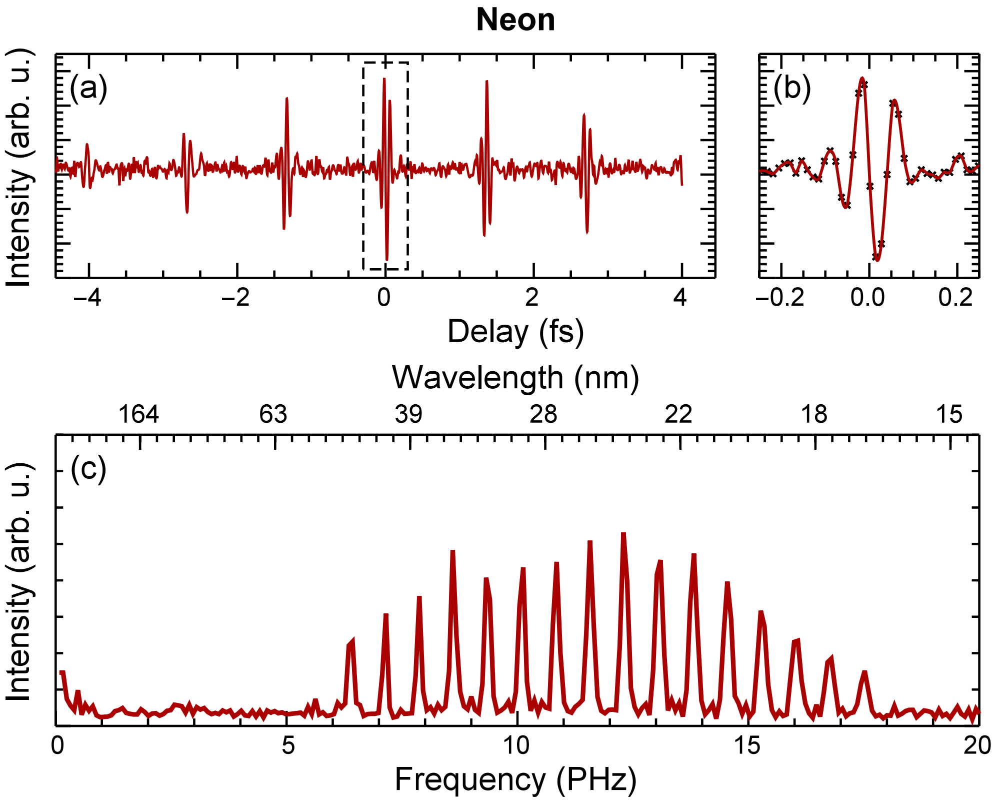
G.S.M. Jansen et al., Optica **3**, 1122 (2016)

HHG Fourier transform spectroscopy

- HHG in Neon yields broader spectra and shorter coherence times.
- HHG detected down to 17 nm wavelength (Al filter cutoff).
- Stability of interferometer and HHG phase coherence maintained at sub-nm level.

HHG-FTS in Neon:

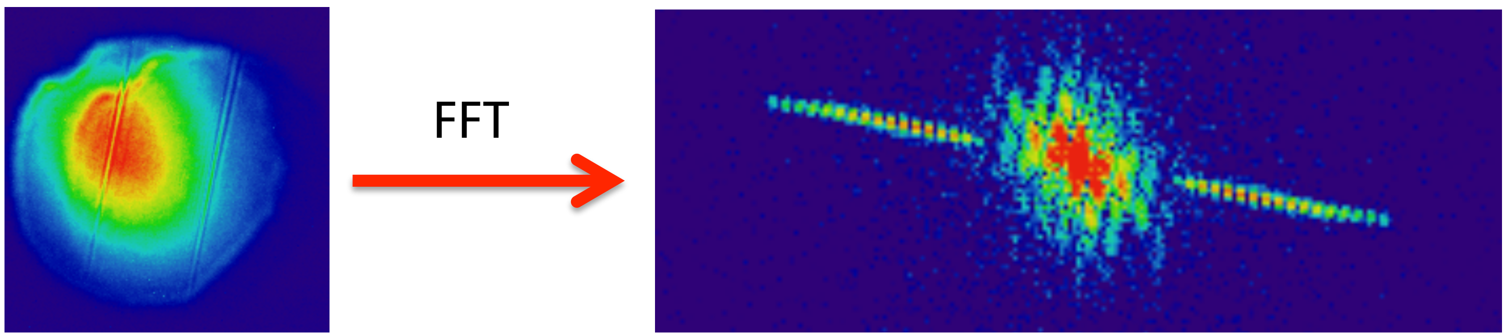




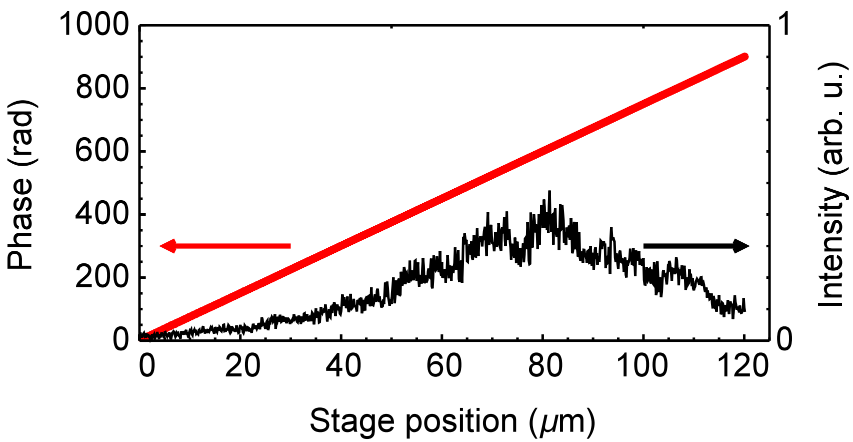
G.S.M. Jansen et al., Optica **3**, 1122 (2016)

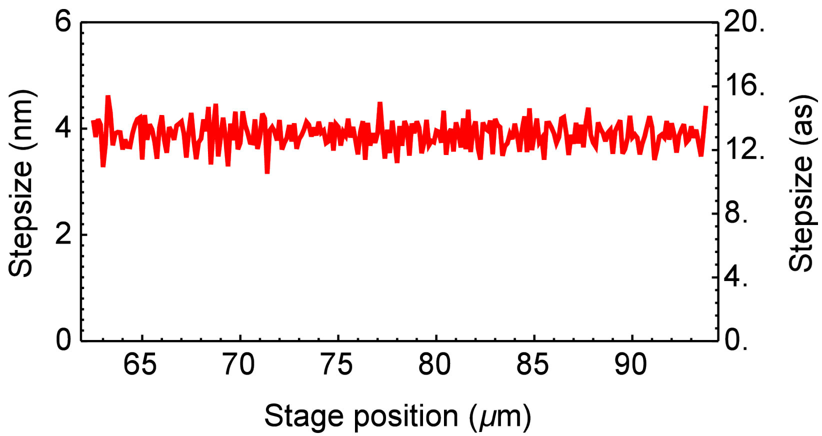
Spatial interference and interferometer stability

Spatial Fourier transform yields a single-shot HHG spectrum:



Phase detection of a single harmonic vs time delay yields timing stability:

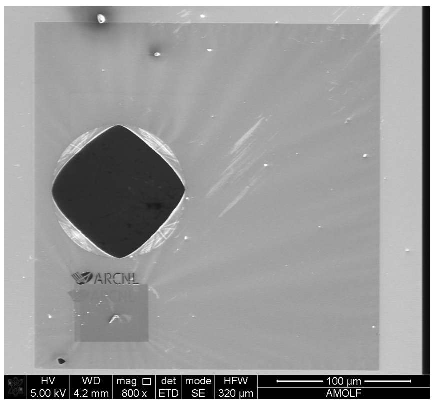


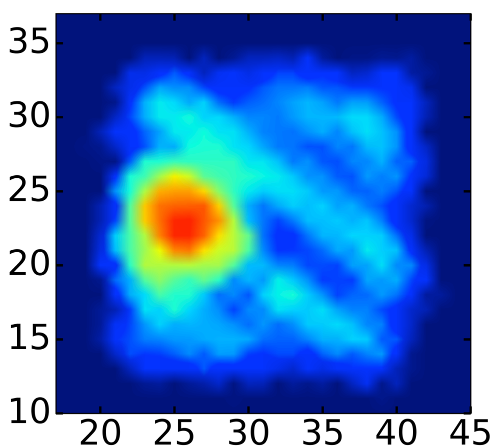


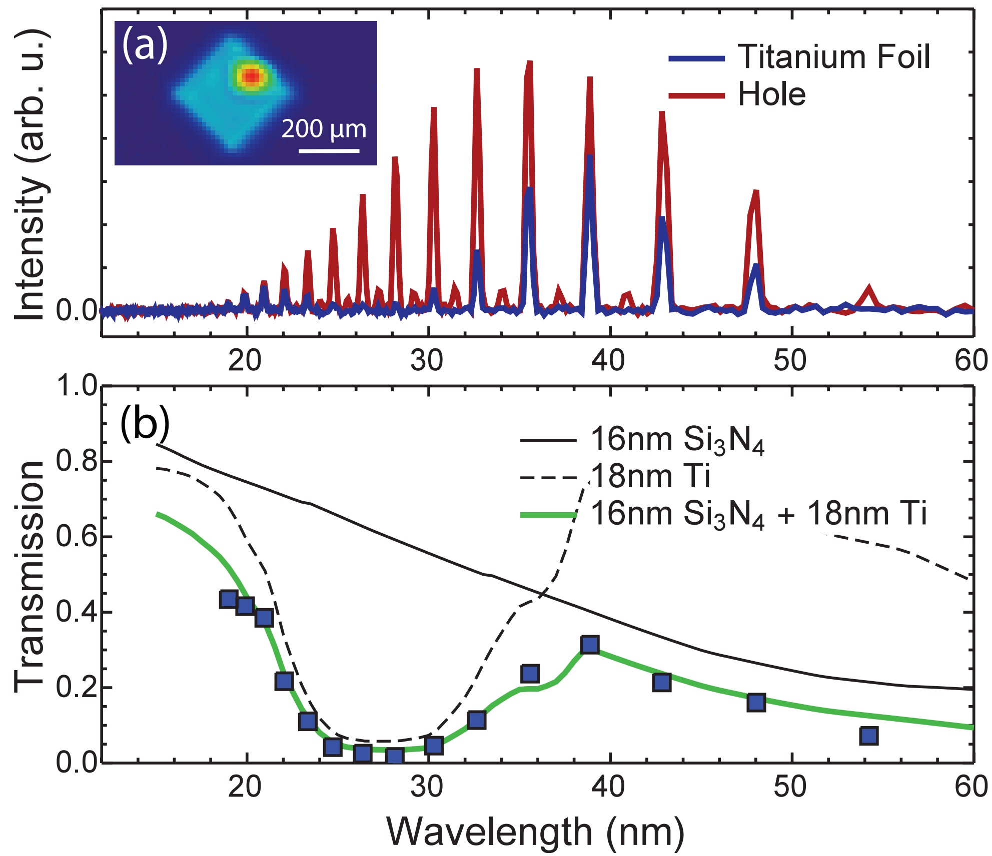
Measured RMS timing stability of 0.8 as, or 0.25 nm optical path length

Spatially resolved XUV spectroscopy

Titanium layer on 250x250 µm silicon nitride foil with a 50 µm hole in it:





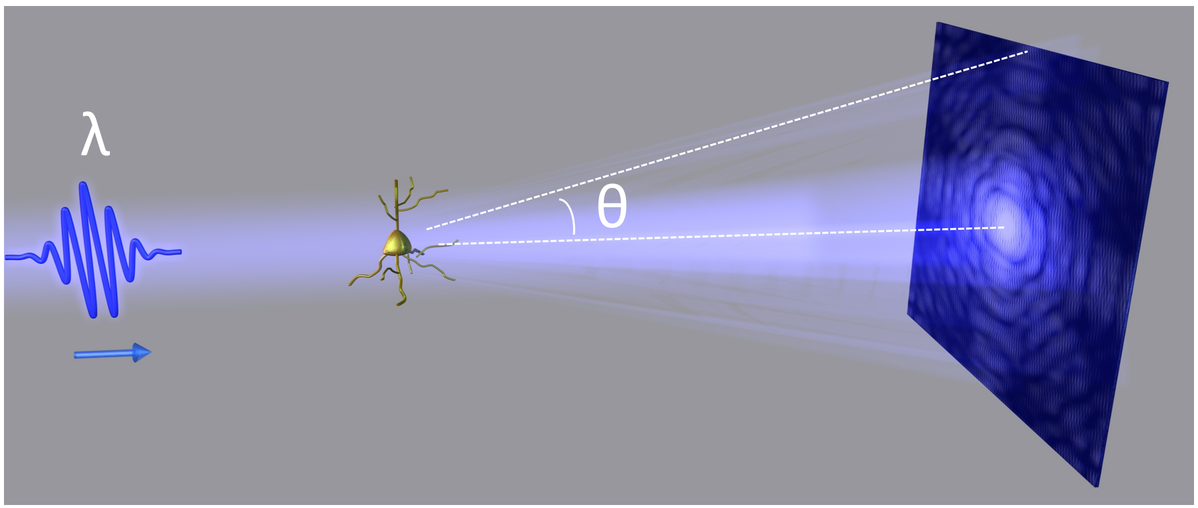


Measurement of the transmitted spectrum of Neon HHG on each CCD pixel

G.S.M. Jansen et al., Optica **3**, 1122 (2016)

Lensless coherent diffractive imaging

Numerical reconstruction of an object from a coherent diffraction pattern, instead of the use of optical components for image formation:



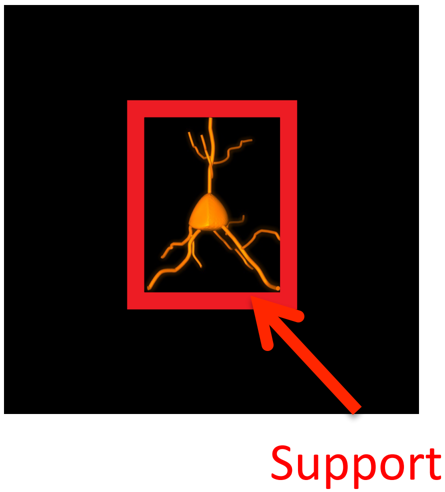
Measured diffraction yields intensity, phase also needed for image reconstruction

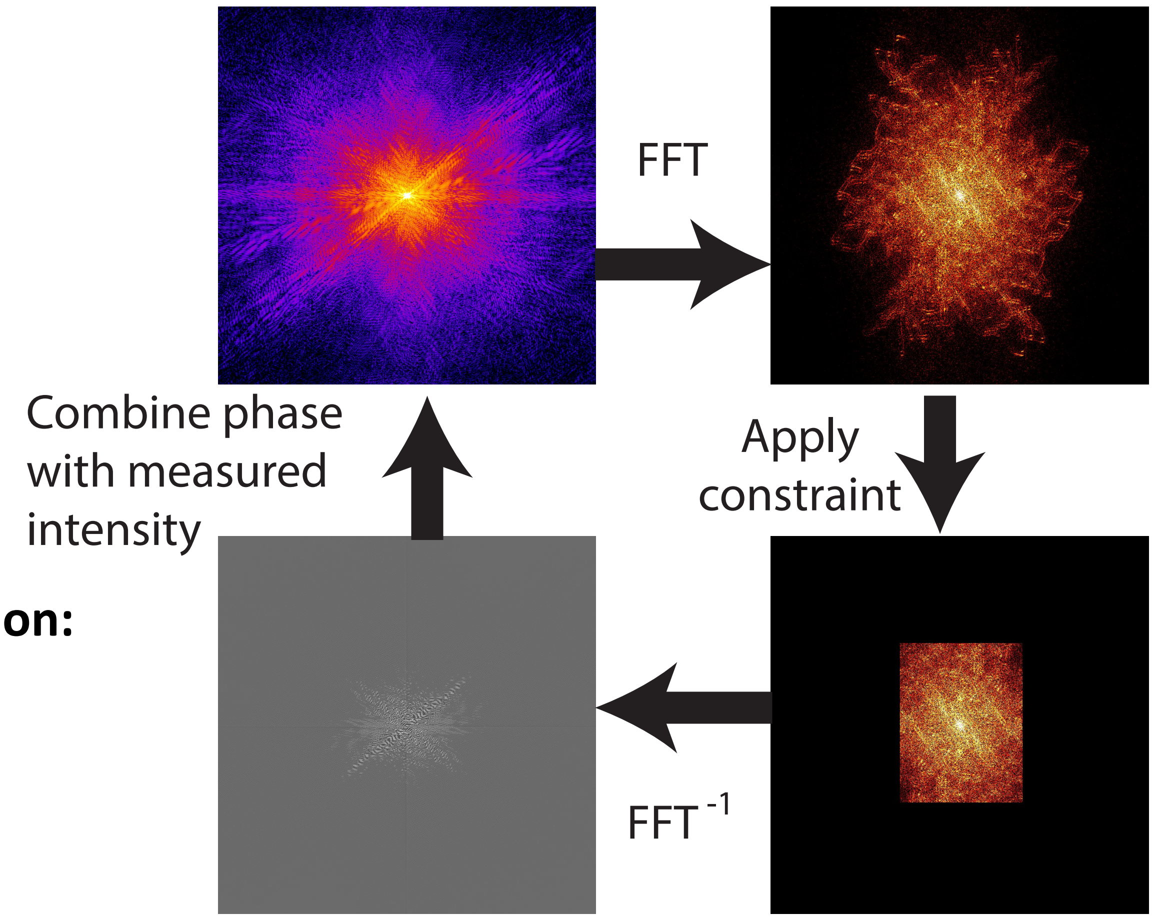
→ The challenge is to retrieve the missing phase information.

- Resolution = $\lambda / 2 \sin \theta$
- High spatial and temporal coherence important.

Image reconstruction from a diffraction pattern

Object:





Needs additional information:

- Finite object support
- Positivity
- Atomicity
- …

Other approaches use multiple measurements instead of an object constraint (ptychography, multi-wavelength/multi-distance phase retrieval, etc.)

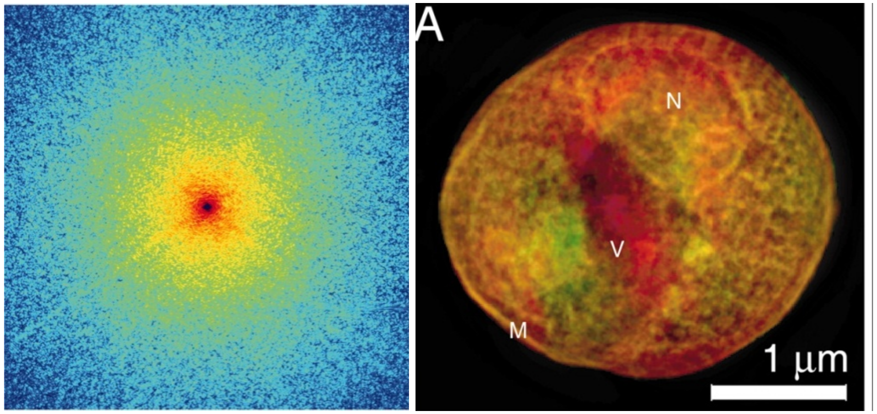
J.R. Fienup, Appl. Opt. **21**, 2758, (1982)

J. Miao et al., Nature **400**, 342 (1999)

Coherent diffractive imaging: examples

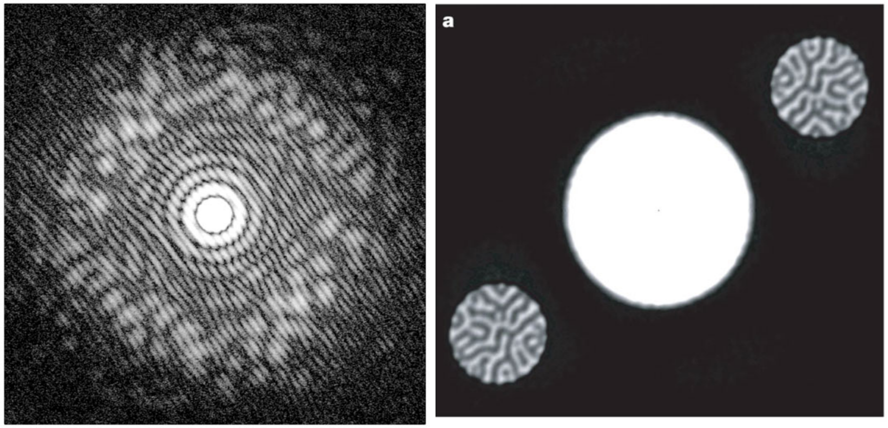
- Several successful experiments have been performed using CDI.
- Resolutions of 20-25 nm achieved.

Freeze-dried yeast cell at 30 nm resolution
Synchrotron, 750 eV photons:



D. Shapiro et al., PNAS **102**, 15343 (2005)

Magnetic nanostructures, 50 nm resolution
Synchrotron, 778 eV photons:

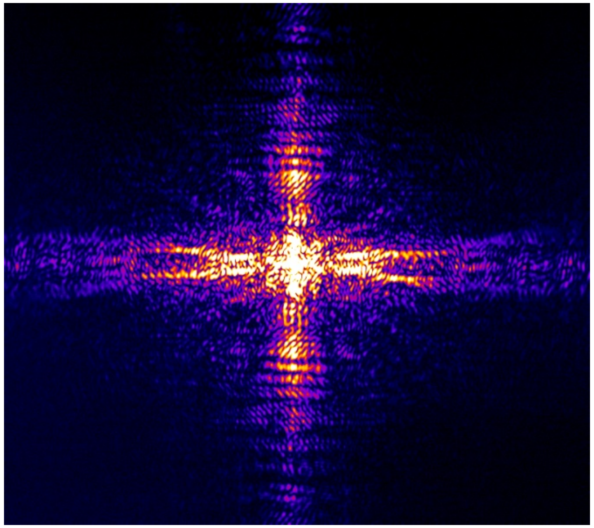


S. Eisebitt et al., Nature **432**, 885 (2004)

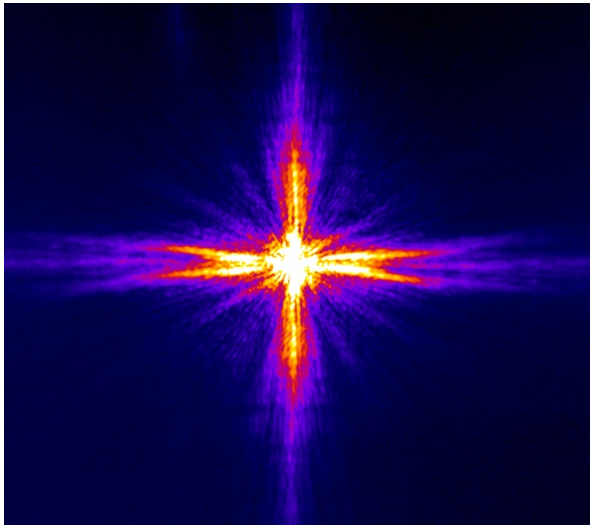
Bandwidth limitations in lensless imaging

- Lensless imaging requires a coherent, monochromatic source, since the diffraction angle is directly proportional to wavelength.
- Broadband sources lead to blurred diffraction patterns:

Monochromatic:



Broadband:



- Limits the resolution, in extreme cases prevents image reconstruction.
- Spectral filtering is possible, but at the cost of serious flux reduction.

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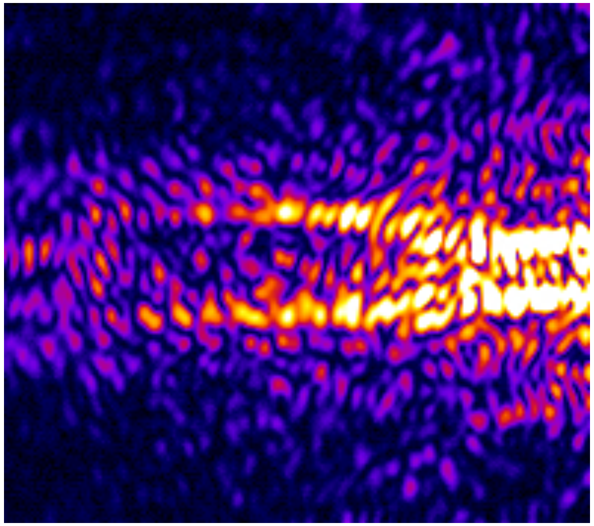
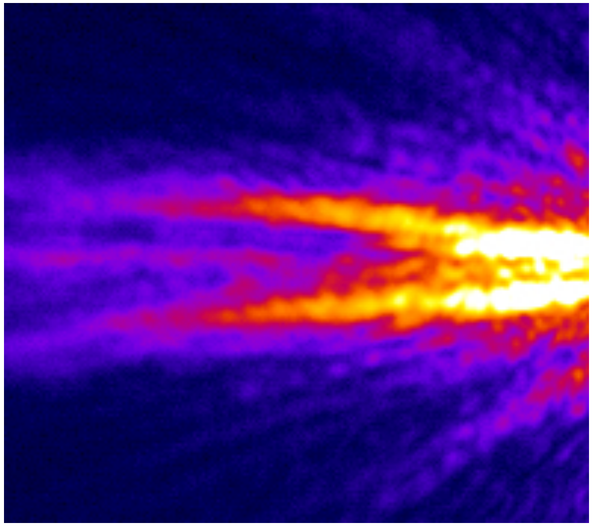


Broadband:



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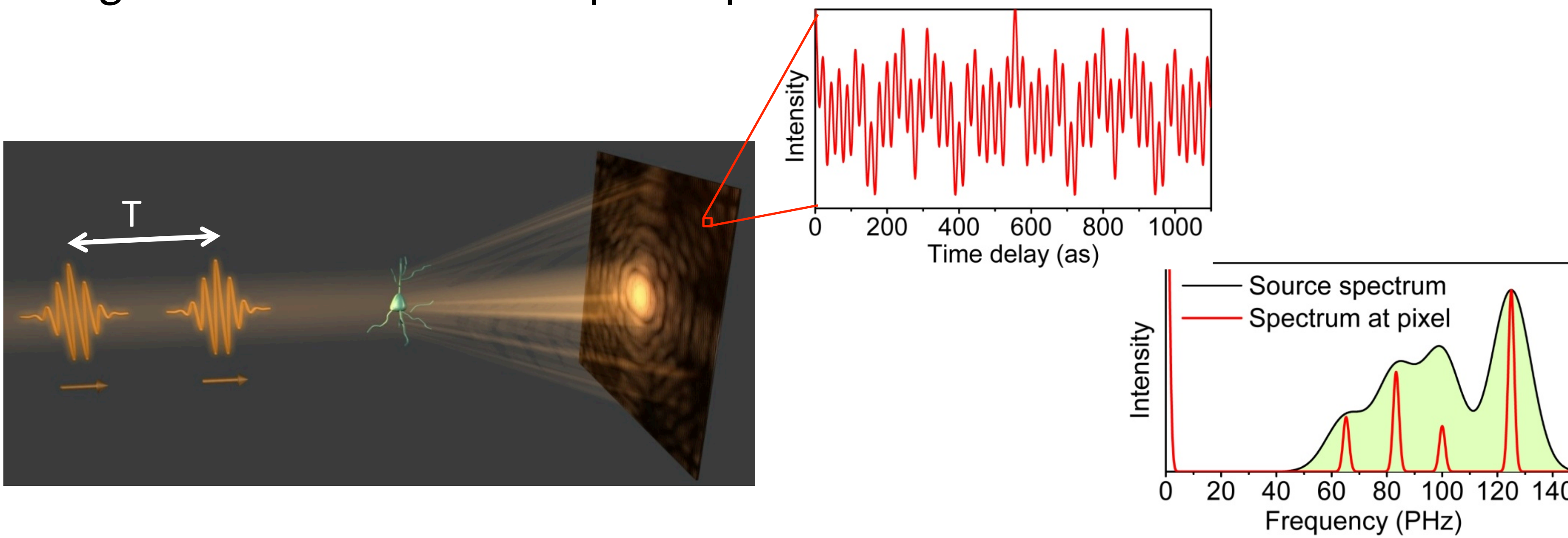
Two-pulse Fourier-transform imaging

- Combination of imaging and Fourier transform spectroscopy
- On each CCD pixel, a Fourier-transform spectrum is recorded of the light diffracted onto that specific pixel.

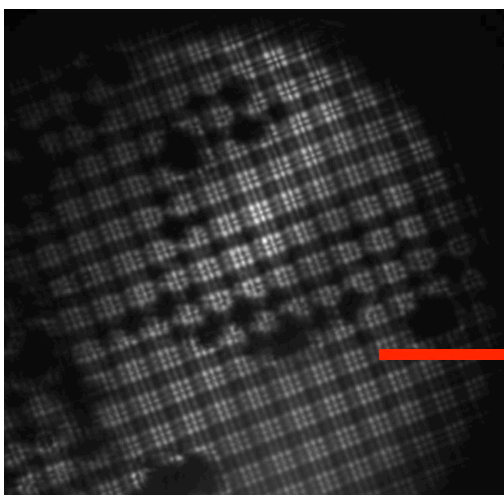


- Allows reconstruction of ‘monochromatic’ diffraction patterns for all spectral components in the pulse.
- The full spectrum is used throughout the entire measurement.

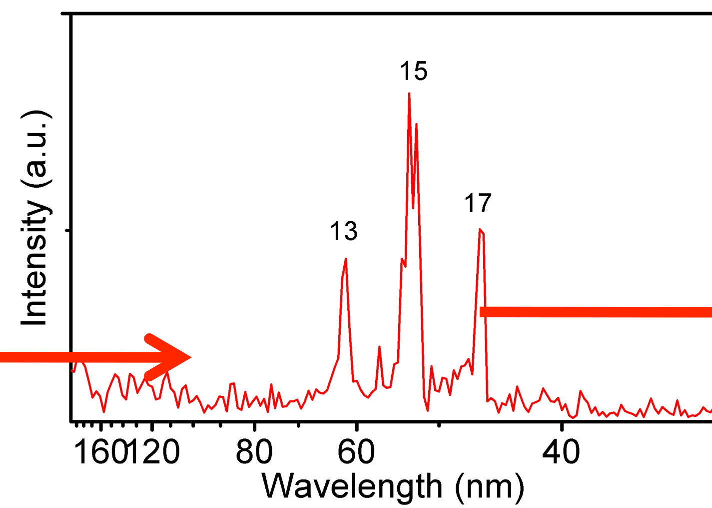
Lensless imaging with XUV radiation

- Sample is a Nickel grid on a 300 nm thick Aluminium foil.
- The Al-foil is partially transparent below 70 nm wavelength.
- Spectrally resolved images at 62, 53 and 47 nm wavelength.
- Scan parameters: 512 steps of 6.6 nm (22 attoseconds).

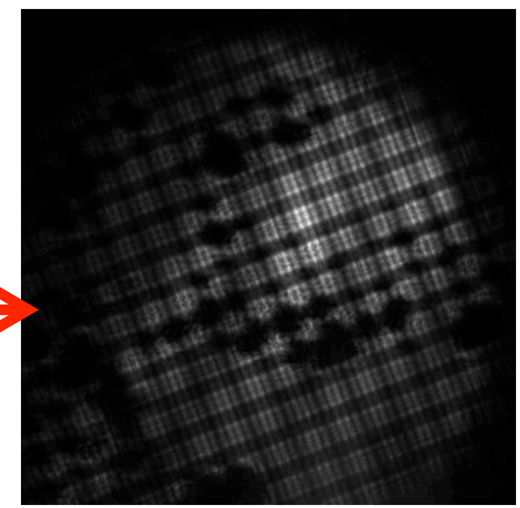
Broadband diffraction:



HHG spectrum:



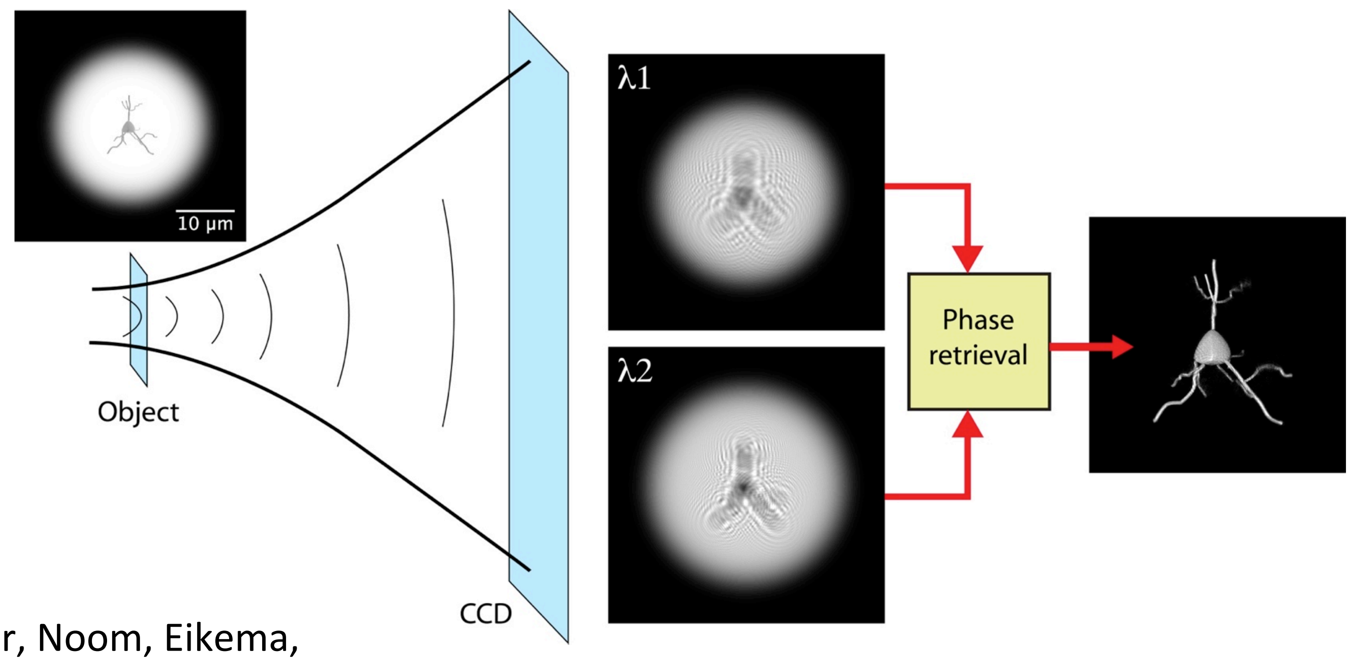
Diffraction at 17th harmonic:



Multi-wavelength iterative phase retrieval

- For Fresnel diffraction, measurements at multiple propagation conditions enable unique image reconstruction.
- The Fresnel diffraction integral describes the field propagation:

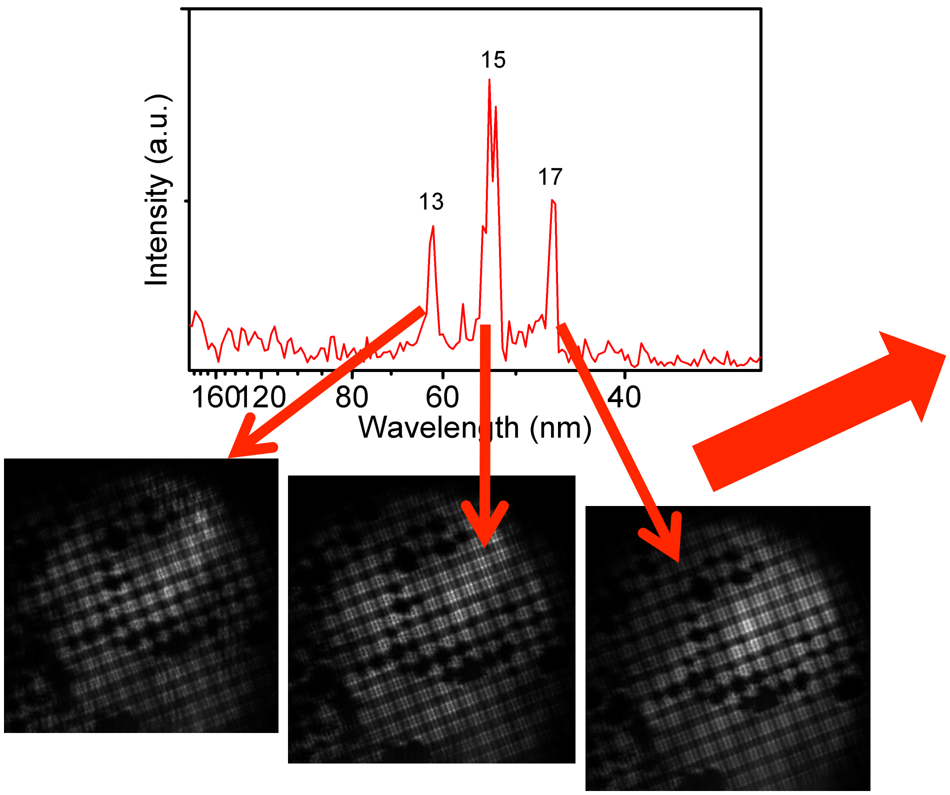
$$E(x,y,z) = \frac{e^{ikz}}{i\lambda z} \iint E(x',y',0)\, e^{\frac{i\pi}{\lambda z}[(x-x')^2+(y-y')^2]} dx'\, dy'$$

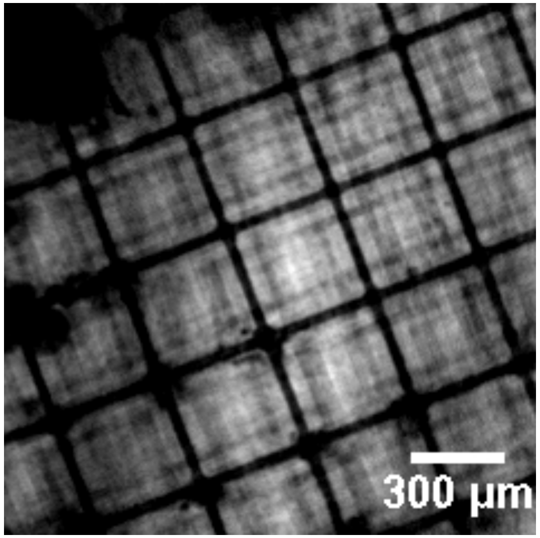


Witte, Tenner, Noom, Eikema,
Light: Sci. Appl. **3**, e163 (2014)

Lensless imaging at short wavelengths

- We use use diffraction patterns at 62 nm, 53 nm and 47 nm as input for our multi-wavelength phase retrieval algorithm.
- Resolution limited by NA to 6.8 µm, can easily be improved in future experiments.





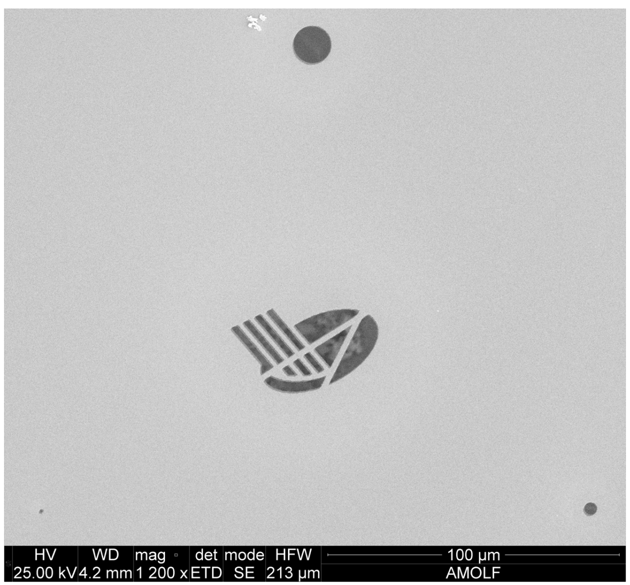
Nickel grid behind
200 nm thick Aluminium layer

Witte, Tenner, Noom, Eikema,
Light: Sci. Appl. **3**, e163 (2014)

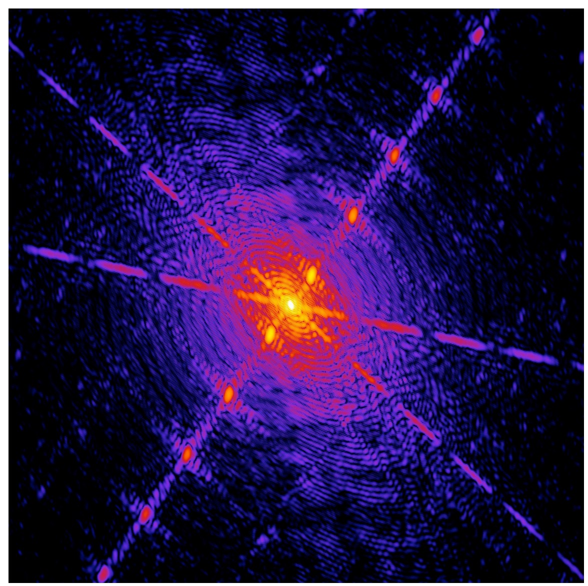
XUV Fourier-transform holography

- Fourier-transform holography provides a direct phase measurement.
- Pinhole-generated reference wave acts as a delta function.
- Signal intensity: $I = \left|E_{ref}\right|^2 + \left|E_{obj}\right|^2 + E_{ref}E^*_{obj} + E^*_{ref}E_{obj}$

Sample



Hologram: $|FT|^2$



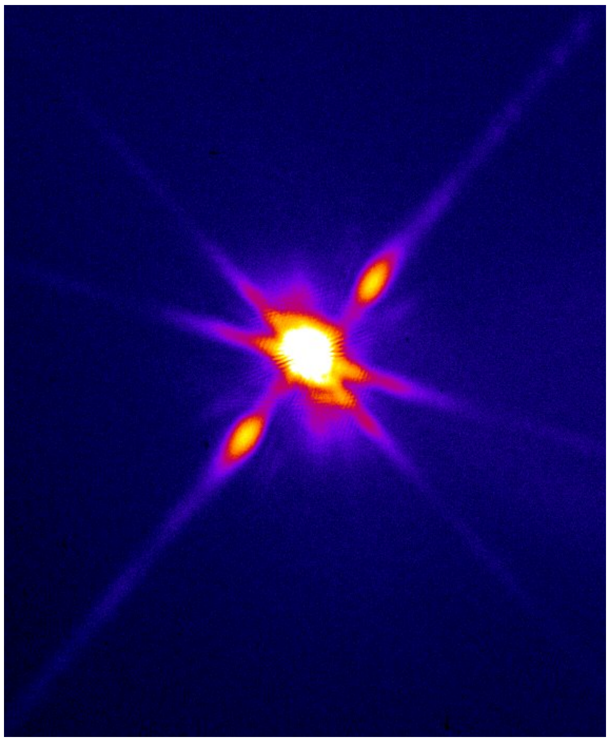
Reconstruction: FT^{-1}

→ Resolution limited by aperture diameter

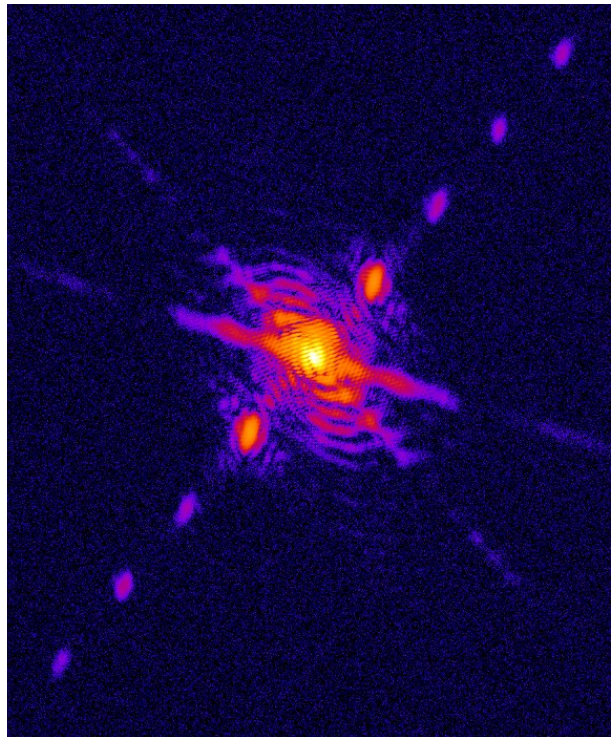
→ Signal proportional to aperture area (~d^2)

XUV holography

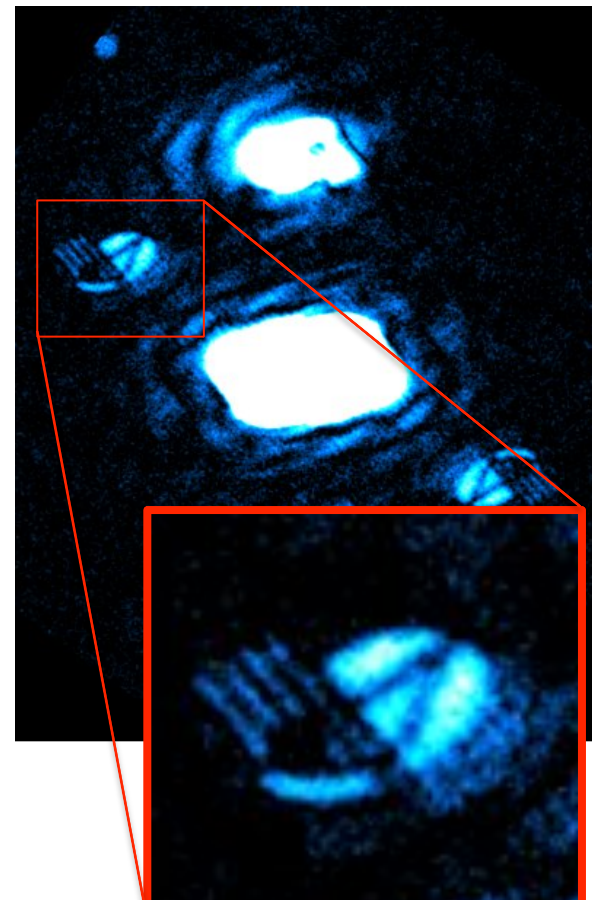
Broadband hologram:



Hologram at λ=33 nm:



Fourier transform:

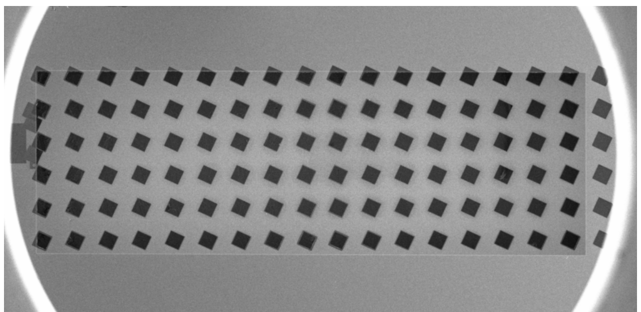


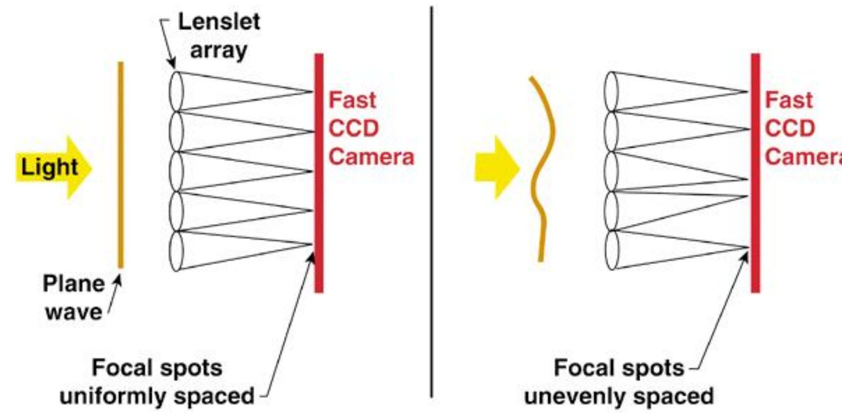
- Signal from smallest pinhole below noise level
- Flux limited by HHG beam size
- Next step: focus the XUV beam

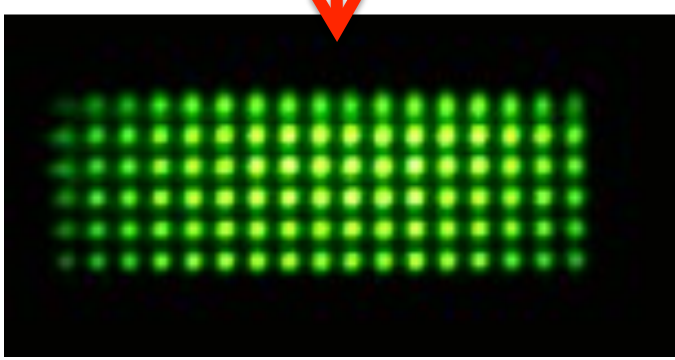
HHG wavefront measurements

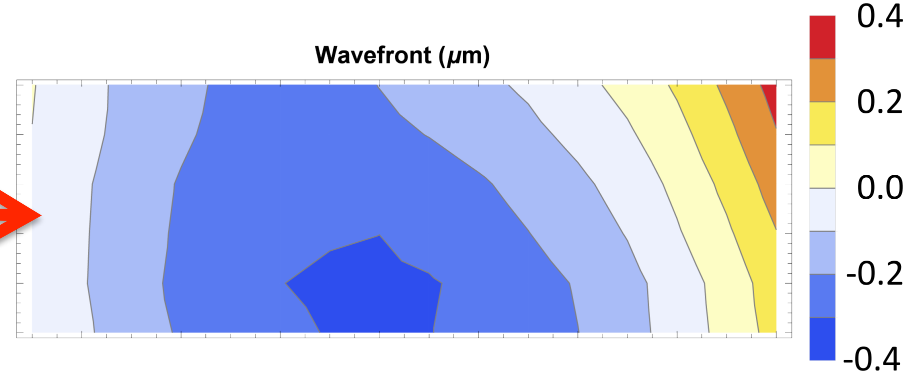
Alternatively, known structures can be used to diagnose the XUV beam itself

Hartmann mask:





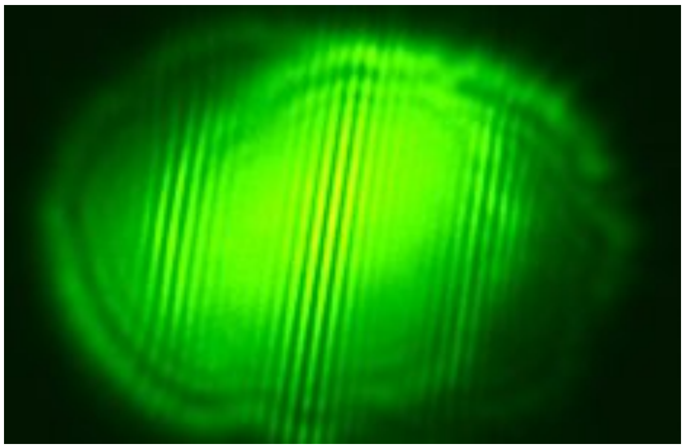




2D wavefront reconstruction, can be combined with two-pulse scan for spectral resolution

HHG wavefront measurements

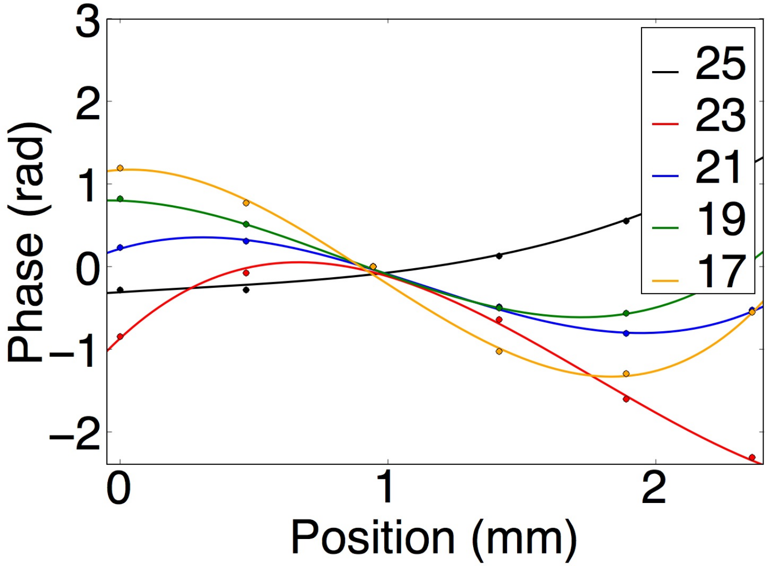
Lateral shearing interferometry: interference of two displaced copies of a HHG beam.



Provides a spatial derivative of the phase:

$$\psi(x) = \varphi(x + \Omega) - \varphi(x)$$

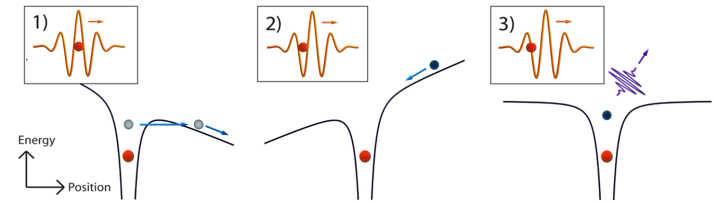
With a known 'shear' Ω, integration yields the spatial phase φ(x)

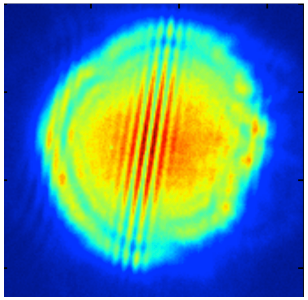


Single-shot spectrally resolved measurement (but 1D information)

Conclusions

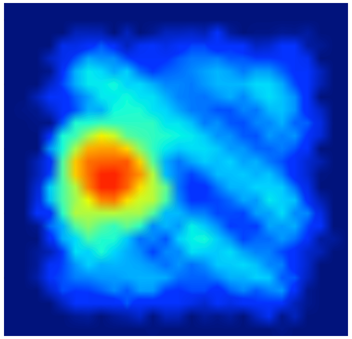
High harmonic generation is a versatile tool for extreme ultraviolet experiments with a table-top setup, such as:

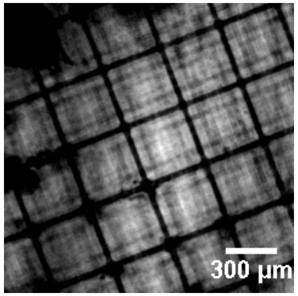




- Interferometry with HHG beams at 17 nm wavelength and beyond.

- Fourier transform spectroscopy with HHG, enabling spatially resolved XUV spectroscopy.





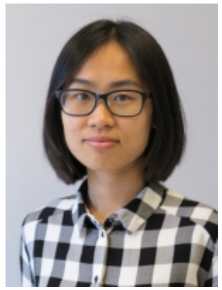
- Spectrally resolved lensless XUV imaging, using the full spectrum and flux of a HHG source.

EUV Generation and Imaging @ ARCNL

PhD students


Tiago Pinto


Lars Freisem


Mengqi Du


Alessandro Antoncecchi


Randy Meijer


Dirk Boonzajer Flaes


Matthijs Jansen

Group leaders


Stefan Witte


Kjeld Eikema

Postdocs


Aneta Stodolna


Denis Rudolf

Technician


Nik Noest

FOM

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European Research Council
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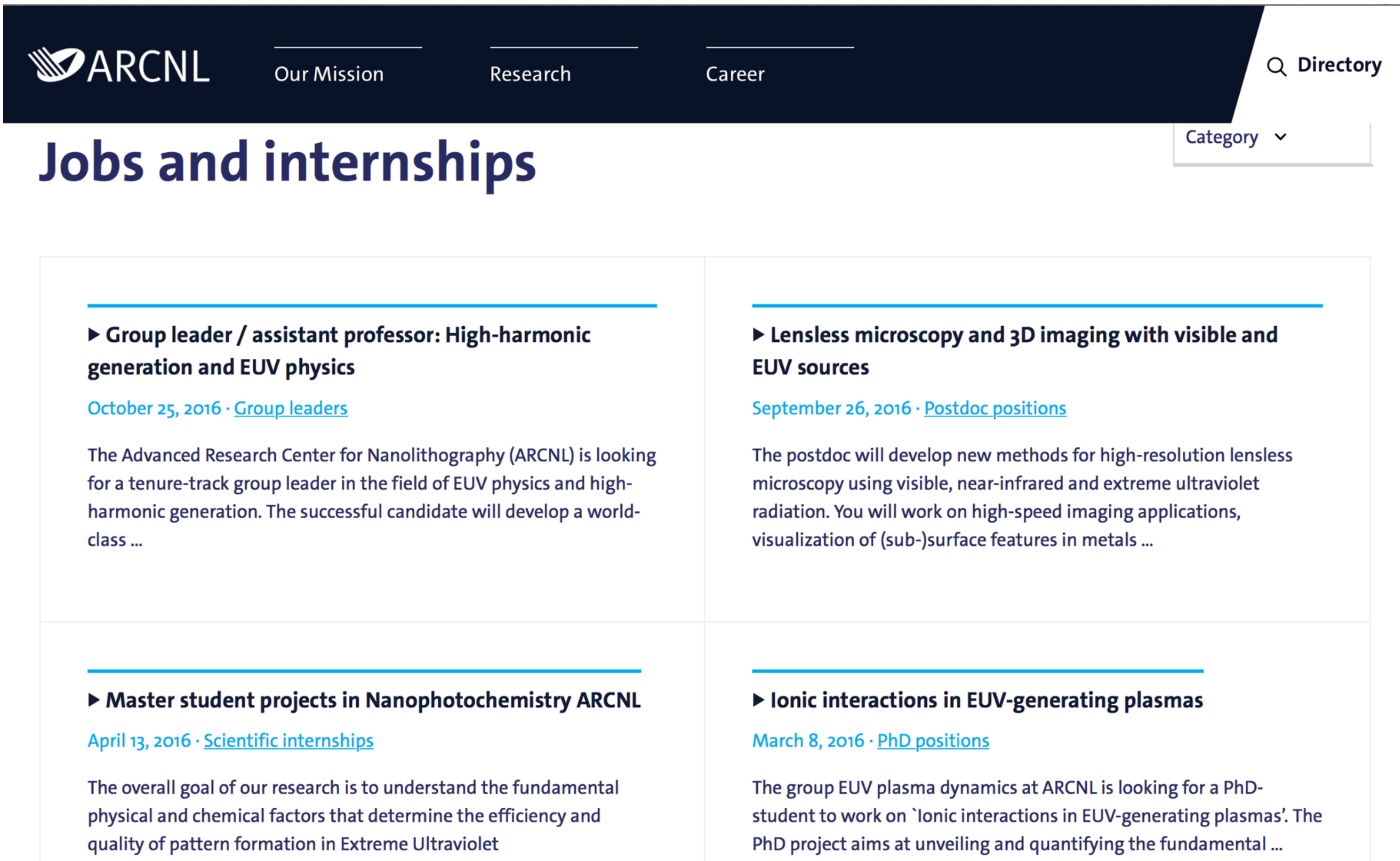

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